

## DEVELOPMENT OF A NUMERICAL MODEL OF A HYPERVELOCITY IMPACT INTO A PRESSURIZED COMPOSITE OVERWRAPPED PRESSURE VESSEL

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### ABSTRACT

#### Introduction

As the outlook for space exploration becomes more ambitious and spacecraft travel deeper into space than ever before, it is increasingly important that propulsion systems perform reliably within the space environment. The increased reliability compels designers to increase design margin at the expense of system mass, which contrasts with the need to limit vehicle mass to maximize payload. Such are the factors that motivate the integration of high specific strength composite materials in the construction of pressure vessels commonly referred to as composite overwrapped pressure vessels (COPV). The COPV consists of a metallic liner for the inner shell of the COPV that is stiff, negates fluid permeation and serves as the anchor for composite laminates or filaments, but the liner itself cannot contain the stresses from the pressurant it contains. The composite-fiber reinforced polymer (CFRP) is wound around the liner using a combination of hoop (circumferential) and helical orientations. Careful consideration of wrap orientation allows the composite to evenly bear structural loading and creates the COPV's characteristic high strength to weight ratio.

As the CFRP overwrap carries most of the stresses induced by pressurization, damage to the overwrap can affect mission duration, mission success and potentially cause loss-of-vehicle/loss-of-crew. For this reason, it is critical to establish a fundamental understanding of the

mechanisms involved in the failure of a stressed composite such as that of the COPV. One of the greatest external threats to the integrity of a spacecraft's COPV is an impact from the meteoroid and orbital debris environments (MMOD). These impacts, even from submillimeter particles, generate extremely high stress states in the CFRP that can damage numerous fibers. As a result of this possibility, initial assumptions in survivability analysis for some human-rated NASA spacecraft have assumed that any alteration of the vessel due to impact is considered a catastrophic failure. This assumption is conservative and made due to lack of knowledge on the level of allowable damage to the composite overwrap that can be sustained and still allow successful completion of the mission. To quantify the allowable damage level to the composite overwrap involves assessing stress redistribution following damage as well as evaluating possible time-dependent mechanisms involved in the COPV response to an impact event.

Limited published work in this subject has shown that COPV can withstand at least some level of damage due to high energy impacts. These observations have been confirmed and expanded upon in recent experimental research performed by NASA. This research has demonstrated that there is not only robustness in a COPV to compensate for CFRP damage, but has also identified two significant failure modes for pressurized COPV. The lowest threshold failure mode involves the perforation of the vessel, and the highest threshold failure mode is the catastrophic rupture. While both of these failure modes mean a loss of the COPV, system robustness affords some tolerance to the venting as opposed to the more catastrophic rupture. As a consequence, it is necessary to understand the conditions that result in the transition between these failure modes.

The aforementioned experimental research has been performed in both the unpressurized and pressurized condition to identify the damage level that triggered the failure threshold. This COPV test program was sponsored by the NASA Engineering and Safety Center (NESC), and tests were performed at NASA White Sands Test Facility (WSTF). Planning and coordination were provided by NASA JSC Hypervelocity Impact Technology (HVIT)

group, and the COPVs were provided by the ISS Program. Unpressurized testing has been conducted at the pressure of the vacuum test chamber, while, the pressurized testing has been conducted at  $290 \pm 10$  bar ( $4,200 \pm 100$  psi) using nitrogen as the pressurizing gas, which corresponds to the design pressure for the target COPV. In this research, spherical aluminum projectiles with varying diameter has been chosen as the impactor.

For the unpressurized COPV, the dependence of penetration up to the dependence of hole size in the liner has been obtained as a function of impact conditions. For the pressurized research, the dependence of penetration up to rupture has been obtained as a function of impact conditions. Two representative post-test photographs of the failed COPV's from a normal impact into the COPV surface are shown in Fig. 1. These images display the dramatic difference between failure modes, venting (Fig. 1a) and rupture (Fig. 1b). For venting, liner perforation, severed composite fibers/tows and ply delamination are commonly observed damage characteristics of this COPV failure mode. In the case of rupture, the COPV typically experienced a separation of its domed regions and severe break-up of the cylindrical region.

Fully understanding the transition from venting to rupture experimentally is costly and potentially unachievable for conditions that cannot be generated in the laboratory. These shortcomings have motivated the performance of three-dimensional numerical simulations to expand the existing experimental database. These simulations have been carried out with the nonlinear-structural-dynamics, analysis-tool, CTH.

A typical pressure contour plot from an impact simulation of an entire COPV is shown in Fig. 2. To generate the COPV stress state without initiating a shock wave, the pressure in the simulated COPV is ramped up to the final pressure over a millisecond prior to impact of the projectile with nitrogen gas. Figure 2a shows the system in this initial condition. After one millisecond, a projectile is initiated into the simulation and impacts the COPV. Figure 2b shows the system after this impact. In the figure, the onset of venting is represented as

the change in pressure ( $\mu\text{bar}$ ), red to green, at the perforation site. Also seen in the figure is the eroded projectile that had passed into the COPV vessel with the generated shock wave in the pressurant propagating just ahead of the material.

In this paper, pertinent experimental details and the development of the material constitutive models necessary for this work along with the efforts to validate their use are discussed. The simulation results are presented and compared with the NASA experimental observations. While work is on-going from this effort, early observations pertinent to the failure threshold are presented.



Fig. 1. Post test photo-documentation of observed failure modes: a) Perforation resulting in venting. b) Remnants of a ruptured COPV due to impact.

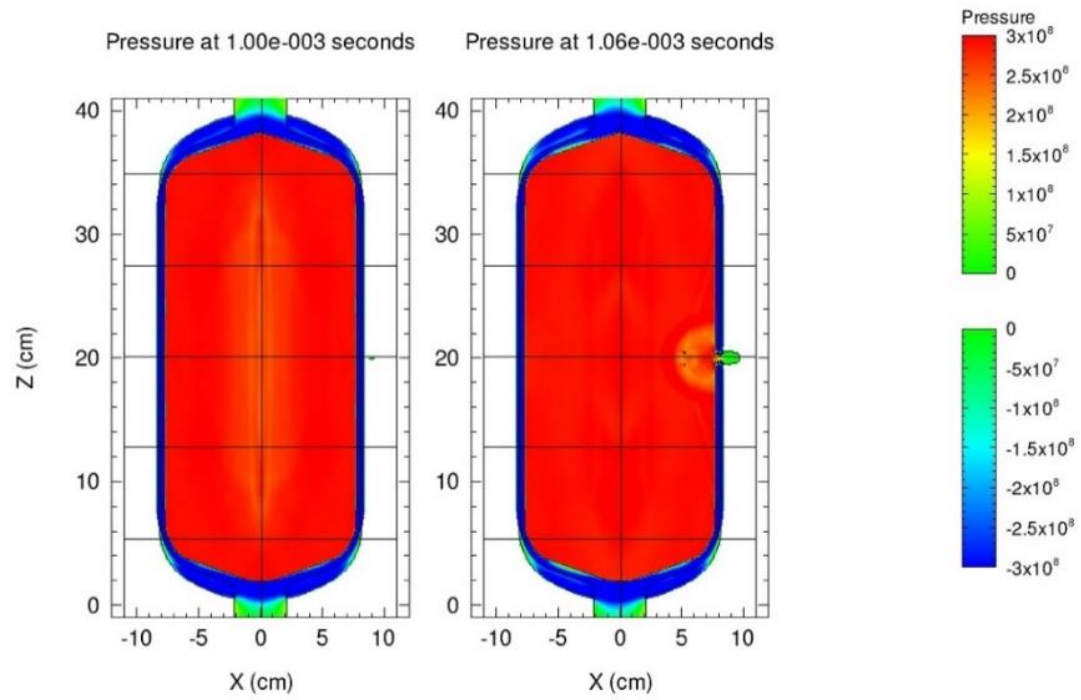


Fig. 2 a) Cross section of pressurized COPV model prior to hypervelocity impact. b) Post-impact showing perforation, venting, projectile erosion and shock wave propagation..